Report on NAG-1-1748

Development and Validation of a Polar Cloud Algorithm for CERES

The objectives of this project, as described in the original proposal, were to develop an algorithm for diagnosing cloud properties over snow- and ice-covered surfaces, particularly at night, using satellite radiances from the Advanced Very High Resolution Radiometer (AVHRR) and High-resolution Infrared Radiation Sounder (HIRS) sensors. Products from this algorithm include a cloud mask and additional cloud properties such as cloud phase, amount, and height. The SIVIS software package, developed as a part of the CERES project, was originally the primary tool used to develop the algorithm, but as it is no longer supported we have had to pursue a new tool to enable the combination and analysis of collocated radiances from AVHRR and HIRS. This turned out to be a much larger endeavor than we expected, but we now have the data sets collocated (with many thanks to B. Baum for the fundamental code) and we have developed a nighttime cloud detection algorithm. Using this algorithm we have also computed realistic-looking cloud fractions from AVHRR brightness temperatures. A method to identify cloud phase has also been implemented. Atmospheric information from the TIROS Operational Vertical Sounder (TOVS) Polar Pathfinder Data Set, which includes temperature and moisture profiles as well as surface information, provides information required for determining cloud-top height.

Clouds existing over snow- and ice-covered surfaces present some unique challenges not encountered in other regions of the globe. They are often difficult to detect in both visible and infrared satellite imagery, and they possesses unusual properties and origins that confound "global" algorithms to retrieve cloud properties. Contrast between clear and overcast scenes is small because clouds have little effect on the planetary albedo of a snow surface, and clouds often reside below surface-based temperature inversions, resulting in little contrast in the infrared wavelengths, as well. The top-of-the-atmosphere cloud forcing, consequently, is much smaller than in other regions of the globe. The effects of clouds on the *surface* energy balance, however, are profound, especially in winter. Clouds greatly increase the amount of downwelling infrared radiation, and substantially reduce the amount of energy lost by the snow/ice surface. The difference between top-of-the-atmosphere and surface cloud forcing in typical Arctic winter conditions for four cloud types is shown in Figure . Note that the TOA forcing can be negative (cooling) for low clouds below the surface-based inversion, as their tops are warmer than the surface. Low clouds, both water and ice, are the predominant cloud type in the Arctic. At the surface, forcing is most sensitive to thin water clouds, especially low ones. The effect of the nearly ubiquitous and difficult-to-detect low ice clouds (so-called "diamond dust") can be as significant as that from water clouds. These unusual attributes of polar clouds make observing them a great challenge, yet obtaining accurate observations is essential owing to their strong influence on the surface energy budget. In addition, validating satellite retrievals presents many obstacles, as few reliable measurements exist, and the long polar night renders some clouds invisible to surface observers. A more complete analysis of cloud forcing in polar (and other) regions can be found in Francis (1999a, submitted).

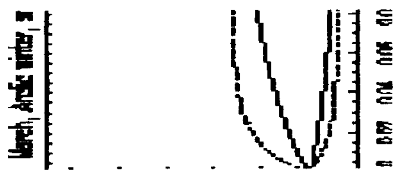

Figure 1: TOA (a) and surface (b) longwave cloud forcing [W m^{-2}] versus liquid/ice water content [g m^{-3}] in typical Arctic winter conditions. Heavy solid line is low ice cloud, light solid line is high ice cloud, short dash is low water cloud, and long dash is high water cloud.

Our efforts to date have focussed on developing a nighttime cloud mask over snow and ice using primarily AVHRR radiances, as the SIVIS software package did not have the capability to incorporate HIRS data in its cloud mask tool before it was abandoned by the CERES cloud working group. Even with the limited information contained in three AVHRR channels, however, the cloud mask performs well, capturing both the "normal" clouds that are colder than the background as well as the "abnormal" clouds that are warmer than the surface. These abnormal clouds occur frequently in polar regions and represent the greatest challenge in determining high-latitude cloud characteristics. The cloud detection algorithm relies on differences in brightness temperatures between the AHVRR channels 3, 4, and 5, which correspond to wavelengths near 3.7, 11, and 12 μm. Cloud particles exhibit different absorption and emission characteristics at these wavelengths depending on the cloud lapse rate, thickness, temperature, and particle phase. These properties are exploited to detect clouds and estimate their bulk properties. Figure illustrates the differences in water and ice absorption versus wavelength, along with the central wavelengths of AVHRR and HIRS channels used in the algorithm. Observed brightness temperatures in two channels with differing amounts of absorption by cloud particles will change relative to each other as the cloud characteristics change. For example, the existence of a cirrus cloud will result in a positive difference between AVHRR channels 3 and 5 at night because clouds are more transparent at 3.7 μm, resulting in more energy from deeper within the cloud (where it is warmer) reaching the satellite in that channel. The opposite occurs in a cloud with an inverted lapse rate, resulting in a negative 3-5 difference.

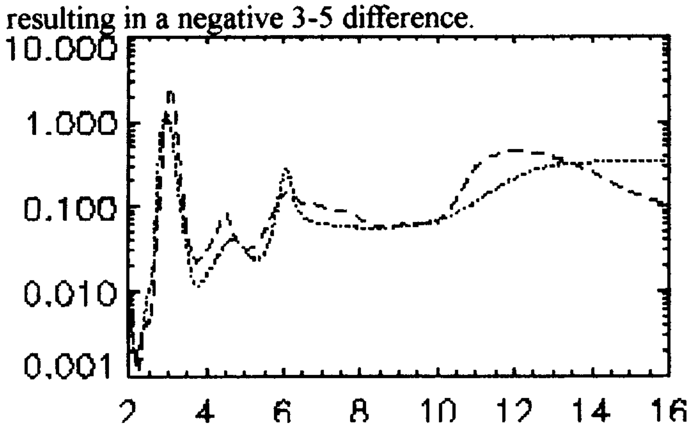

Figure 1: Absorption coefficients of ice (dashed line) and water (dotted) versus wavelength. Central wavelengths of HIRS and AVHRR channels used in the algorithm are indicated

Several AVHRR orbits from NOAA-9 during October 1, 1986, were used to develop and test the AVHRR-based cloud mask. A variety of nighttime situations over Arctic and Antarctic sea ice and snow illustrate several typical cloud types, including normal clouds that are colder than the surface and abnormal clouds that are either warmer than or nearly indistinguishable from the surface in infrared imagery. Figure

Figure 1: Example of an AVHRR orbital swath in the Arctic Ocean at 21 UTC on 1 October 1986. Reds are warm areas and blues are high values of channel 3-5 (3.7 μm - 12 μm).

presents an example of an orbit over the Arctic ocean on October 1, 1986. This simple combination of the AVHRR 12-μm channel and the 3.7 - 12 μm difference highlights most of the cloud features to the eye. The light blue area in the upper left is contaminated by solar radiation, and is not of interest in this study, as clouds are relatively easy to detect when solar channels are available. In the rest of the image, red areas are relatively warm according to AVHRR channel 5 and can be either clear or can contain "abnormal" clouds. Light blue areas are a crude display of cold clouds. In Fig. the results of the cloud detection algorithm are presented. Comparing this to Fig. , one cans see that the cloud identification algorithm, which includes 4 tests involving thresholds with AVHRR channels 3, 4, and 5, works well. One of the tests designed to detect "normal" clouds is displayed in Fig. , while a test for "abnormal" clouds appears in Fig. . It is apparent that "abnormal" clouds constitute a significant fraction of clouds in the Arctic, which is why algorithms that assume clouds are always colder than the surface routinely fail (such as ISCCP, see Fig.).

The AVHRR channel 3 (3.7 μm) is fairly noisy owing to the cold temperatures of the polar regions, so the use of the corresponding HIRS channel (19), with its larger pixel size and resulting higher signal-to-noise ratio, is a valuable aid in removing erroneous clouds caused by this noise. Further validation using surface-based observations during the 1997/1998 Surface Heat Budget of the Arctic (SHEBA) field experiment, which included cloud lidar and radar, will provide additional information. We plan this work for the coming year when we acquire TOVS data for this time and location, as conventional surface-based cloud observations, particularly during nighttime, are problematic. Not only is it often difficult for observers to see clouds at night, but surface observations are a bottom-up perspective while satellites see from the top down, and satellites see an "effective cloud fraction," which is a combined effect of the cloud cover and its emissivity.

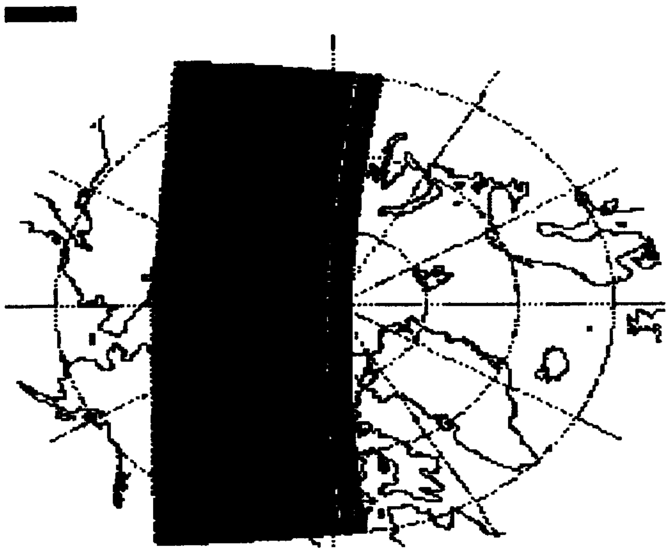

Figure 1: Example of the 3-channel AVHRR cloud identification algorithm for 1 October 1986 at 21 UTC using all four cloud tests. Red is clear, blue is cloudy.

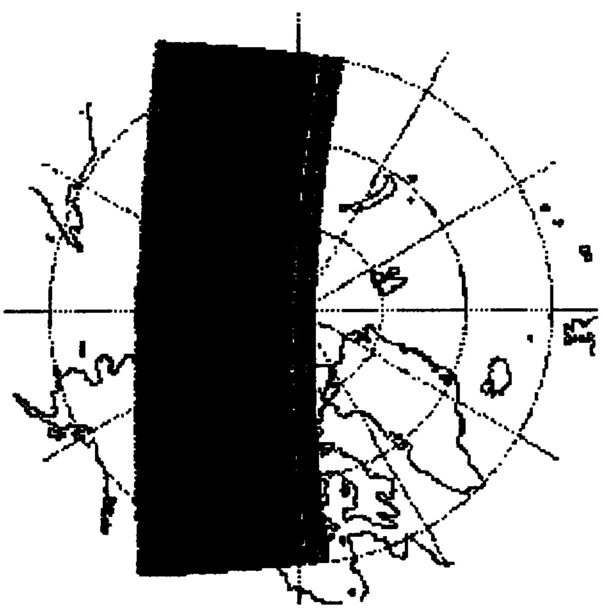

Figure 1: As in Fig. but a test for "normal" clouds only using the AVHRR channel 3-5 difference.

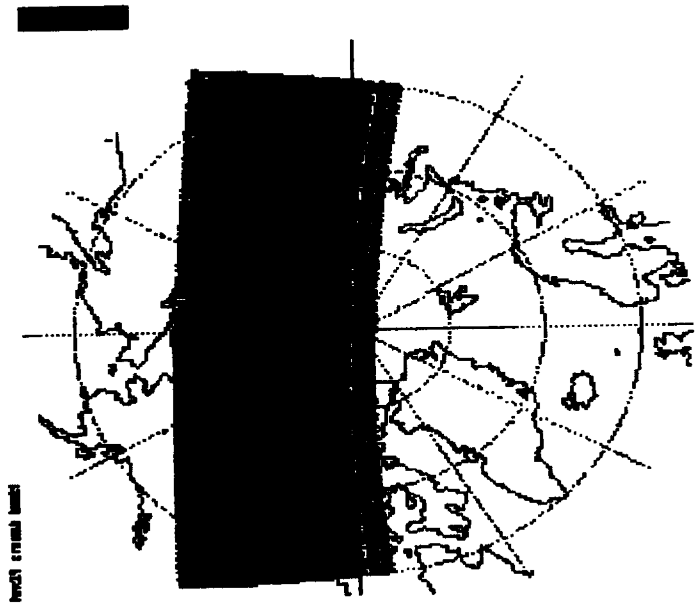

Figure 1: As in Fig. but a test for “abnormal” clouds only using the AVHRR channel 3-5 difference.

Another interesting example is presented in Fig. , which shows the area around Greenland. This is a challenging case because of the low stratus cloud over the unfrozen northern Baffin Bay that is apparently being advected onto the Greenland ice sheet just south of Thule (“**X**” in Figure a). The cloud is apparently transforming from one that is colder than the water surface to one that is warmer than the ice surface as it ascends the ice cap. The cloud mask easily captures the low stratus over open water and the warm cloud over the ice, but has some difficulty identifying it in its transition period.

Figure 1: Cloud mask results for an area near Greenland at 0900 UTC on 1 October 1986. Colors are associated with each of the 4 cloud tests

The addition of HIRS data to AVHRR affords many opportunities to diagnose other bulk cloud properties, as additional spectral information is available, and channels in the near-IR have a better signal-to-noise ratio owing to their larger FOVs (17 km at nadir versus AVHRR's 1 km). We use the additional spectral information in HIRS to estimate cloud phase, cloud-top height, and cloud thickness. We also obtain a cloud fraction estimate within each HIRS FOV using the AVHRR pixels contained in it. Figure is an example of the cloud fraction retrieval for the same orbit shown in Fig. .

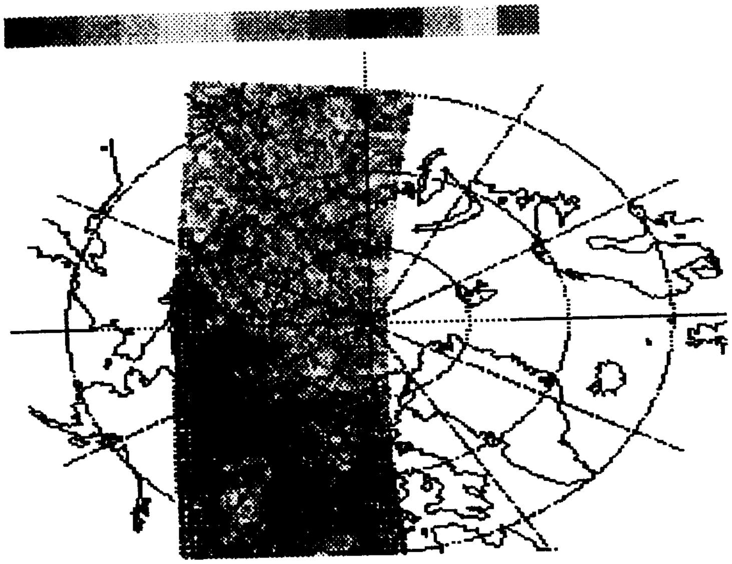

Figure 1: Example of cloud fraction retrieval within each HIRS FOV using AVHRR brightness temperatures. Predominantly red areas in the upper left are contaminated by solar radiation and should be disregarded.

Table presents a summary of the AVHRR and HIRS channels that are used to determine additional cloud properties.

Cloud phase. Two pairs of HIRS channels aid in the determination of cloud phase. The difference between the 8.3 and 11 μm channels is sensitive to phase owing to differences in the absorption coefficient (Fig.). This difference is relatively large for ice clouds and small for water clouds. An example for the same October 1, 1986 orbit is shown in Fig. .

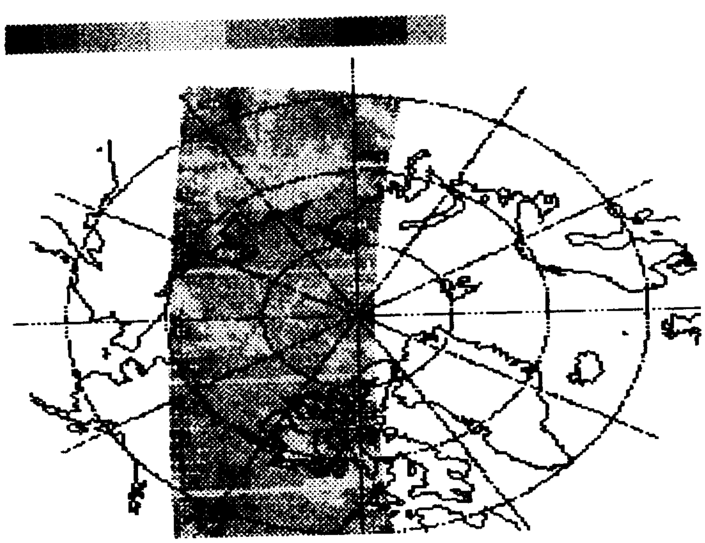

Figure 1: Difference in brightness temperature between HIRS channels 10 (8.3 μm) and 8 (12 μm) for 1 October 1986 at 21 UTC over the Arctic. High values of the difference suggest ice-topped clouds (or ice-covered surface where clouds are absent) and low values are indicative of water clouds.

In areas that are determined to be cloud-covered, high values of this difference are ice-topped clouds, and low values tend to be made of liquid water. To help resolve any ambiguity, the difference between the 3.7 and 4.0 μm is also a useful indicator, as it is sensitive to particle size: water clouds with their smaller particles are more effective emitters at 3.7 μm, thus this difference is larger for water clouds. The test used in this algorithm to identify cloud phase is if $T_B(8.3\mu m) - T_B(11.1\mu m) > -1$ then the cloud-top is assumed to be composed predominantly of ice particles.

Cloud-top height. A popular technique for estimating cloud-top height is the CO_2-slicing method developed at the University of Wisconsin. This algorithm, however, does not work well with low clouds, which happens to be the most common cloud type in the Arctic. The Improved Initialization Inversion algorithm ("3I") from the French LMD group (3I was developed to process TOVS sounding data) includes a cloud-top retrieval method whose accuracy for low-cloud heights has been recently improved. In fact, cloud amounts contained in the TOVS Pathfinder data set, which are retrieved using this method, are the first satellite retrievals that compare well with surface observations in the central Arctic. Figure illustrates the good agreement between monthly-mean TOVS/3I-derived cloud amounts and surface-observed cloud fractions over the central Arctic Ocean (Schweiger *et al*, 1999), and compares these retrievals to those from the reprocessed ISCCP D-2 data set.

As a follow-on to this project, the 3I technique will be adapted and incorporated into our algorithm for retrieving cloud height. Any cloud-height retrieval method requires knowledge of the atmospheric temperature and moisture structure. In this application, atmospheric information is ingested from the recently produced TOVS Polar Pathfinder Data Set for the Arctic (Schweiger and Francis, 1999), which is produced from TOVS radiances over the Arctic region using the 3I algorithm. This technique has been modified to improve the accuracy in polar conditions (Francis, 1994). Temperature profiles, humidity profiles, surface temperature, and surface type (land/sea ice/open water) are extracted from the data set. This information will allow us to adapt the cloud-top retrieval algorithm used in 3I to individual HIRS fields-of-view (FOVs). Validation data are obtained from Russian ice stations (for the October 1986 test data set), and in the near future we will use surface-based remote sensing observations from the 1997/1998 Surface Heat Budget of the Arctic (SHEBA) field experiment when Pathfinder data for this recent period are processed.

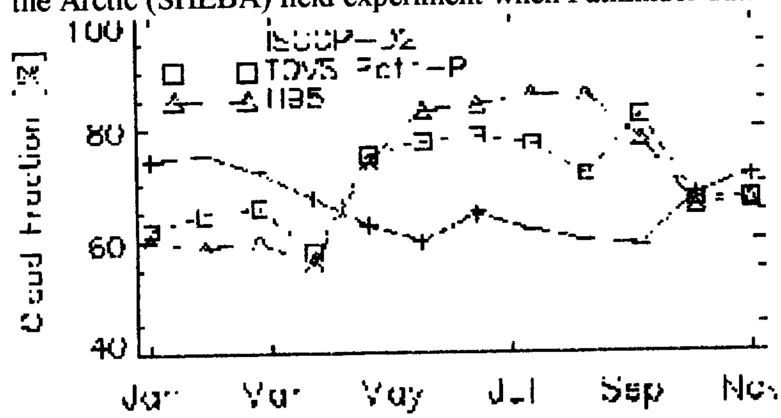

Figure 1: A comparison of monthly-mean surface-observed (H95) cloud fractions to two satellite-retrieved cloud fractions over the Central Arctic Ocean. The ISCCP-D2 data set is a reprocessed version of the original International Satellite Cloud Climatology Project product, and the TOVS Path-P is the cloud fraction retrieved using the revised 3I algorithm.

the TOA and surface. *J. Atmos. Sci.*, submitted.

In summary, efforts on this project to date have produced what appears to be a satisfactory nighttime cloud detection scheme for snow- and ice-covered regions. We are able to distinguish cloud phase, and estimate cloud fraction within each HIRS FOV. In the future we will adapt the algorithm to retrieve cloud height from the 3I software (which operates on arrays of HIRS FOVs) to our application, and then validate its results with surface-based observations from conventional data sets as well as those from the recent SHEBA field program.

Table 1: Summary of AVHRR and HIRS channels used to infer cloud properties.

Channels	Advantages	Disadvantages
AVHRR 3-5 (3.7 - 12 μm)	□ High sensitivity to clouds □ IR scattering in Ch. 3 -- aids detection of water clouds	□ Solar contamination in daylight □ IR scattering in Ch. 3 -- complicates interpretation of signal □ Low signal-to-noise in Ch. 3 over polar areas
AVHRR 4-5 (11 - 12 μm)	□ Works day and night □ Little IR scattering	□ Less sensitivity than 3-5
HIRS 19 - 8 (3.7 - 11 μm)	□ Similar to AVHRR 3-4 □ Ch. 19 has less noise than AVHRR Ch. 3 □ Use to remove "noise clouds" detected by AVHRR Ch. 3-5	□ Lower resolution than AVHRR (17 km versus 5 or 1 km)
HIRS 19-18 (3.7 - 4 μm)	□ Detects water clouds in day and night	□ Solar contamination complicates interpretation
HIRS 10-8 (8.3 - 11 μm)	□ Detects cloud phase in day and night	□ Some ambiguity due to weighting function peak differences
HIRS 6-15 (13.7-4.46 μm)	□ Used to estimate cloud thickness	□ Saturates for thick clouds

References and Related Papers/Presentations

Francis, J.A., 1999a: Effects of cloud properties and surface characteristics on cloud forcing at the TOA and surface. *J. Atmos. Sci.*, submitted.

Francis, J.A., 1999b *(invited)*: Polar clouds: Now you see them, now you don't. *IUGG General Assembly,* 18-30 July 1999, Birmingham, U.K.

Francis, J.A., 1999c: Cloud radiative forcing over Arctic surfaces. 5th Conference on Polar Meteorology and Oceanography, Am. Meteor. Soc., 10-15 Jan. 1999, Dallas, TX.

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